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Foot Disorders Associated with Over-Pronated and Over-Supinated Foot Function:The Johnston County Osteoarthritis Project

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Abstract

Background—The occurrence of musculoskeletal foot disorders differs by race and obesity, and these disorders may be related to pronated (low arch) or supinated (high arch) foot function. This cross-sectional analysis examined relationships of foot disorders and foot function by race and obesity in a community-based observational study of adults 50+ years old with and without osteoarthritis.

Methods—Members of a prospective cohort study in North Carolina were included in this analysis (N=1466, 67.2% women, 29.5% African American, mean age 68.5 years). Foot disorders were identified with a validated assessment tool, and each foot was categorized as over-pronated, over-supinated, and referent using the center of pressure excursion index from foot pressure scans during normal-paced walking. Logistic regression models estimated associations between foot function and each foot disorder with age, body mass index (BMI), gender, and race as covariates.

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Results—Compared to referent, an over-pronated foot was associated with hallux valgus (adjusted odds ratio [aOR] 1.36, 95% confidence interval [CI] 1.13-1.65) and overlapping toes (aOR 1.36, 95% CI 1.12-1.64), especially in the obese. An over-supinated foot was inversely associated with hallux valgus (aOR 0.85, 95% CI 0.74-0.97). An over-supinated foot was less likely to be associated with Tailor's bunions among the obese and was more likely to be associated with plantar fasciitis in Caucasians.

Conclusion—Foot function was related to hallux valgus and overlapping toes, especially among the obese. In clinical patients as well as in the community of older adults, treatments for both the foot disorder and the pronated/supinated foot are needed.

Level of Evidence—Level II-2: Evidence obtained from well-designed cohort study.

Keywords

foot; foot disorders; epidemiology; biomechanics; pronation; supination

INTRODUCTION

Musculoskeletal foot disorders are common among older adults, with estimates suggesting that more than 60% may be affected. The prevalence of these disorders has been shown to vary by race[7, 9] and obesity,[4, 8, 9, 22] with Caucasians more likely to have Tailor's bunions than African Americans; among the non-obese, African Americans are more likely to present with hallux valgus, hammer toes, and overlapping toes than Caucasians; among obese persons, a potentially lower prevalence of hallux valgus may occur compared to non-obese persons. Foot disorders are associated with foot symptoms, impaired balance and fall risk, and disability,[1, 4, 20, 21, 24] but their etiology is not well understood. Biomechanics of the foot during functional activities, such as walking, may play a role in the development and progression of foot disorders. Most prior reports of foot disorders and foot function (pronated [low arch] and supinated [high arch]) suggest a plausible association,[3, 5, 16, 17, 27] although these studies are frequently limited by samples that may not be representative of the general population. Recently, Hagedorn et al.[11] examined the association between foot function (based on plantar pressure data) and foot disorders (based on a validated assessment tool) in a large, population based study of over 3,000 Caucasian men and women from the Framingham Foot Study. In their sample, compared to feet without extreme foot function (not pronated or supinated), those with a pronated foot were more likely to have hallux valgus and overlapping toes and those with a supinated foot were less likely to have hallux valgus. Since race and obesity also are important factors associated with foot disorders, the next step to further elucidate individuals from the general population who are at high risk for foot disorders is to examine these foot function - foot disorder associations among different racial and body weight subgroups.

The primary purpose of this study was to determine whether specific musculoskeletal foot disorders were associated with over-pronated and over-supinated feet in a large, community-based cohort of Caucasian and African American men and women who were normal weight, overweight, and obese. A secondary objective was to examine whether relationships of foot

disorders and foot function differed by race (African American and Caucasian) and body mass index category (normal weight, overweight, and obese).

MATERIALS AND METHODS

Study Participants

Participants were from the Johnston County Osteoarthritis Project. This project is an ongoing, prospective, community-based longitudinal study in African Americans and Caucasians with and without osteoarthritis residing in six townships in Johnston County, North Carolina. Civilian, non-institutionalized residents 45+ years old were enrolled between 1991 and 1997, and additional residents 45+ years old were enrolled during 2003-2004. [15] From 2006 to 2010, 1,695 participants completed clinical examinations during a follow-up visit, and by the time of this visit, participants were at least 50 years old. The Johnston County Osteoarthritis Project has been continually approved by the Institutional Review Board of the University of North Carolina at Chapel Hill and the Centers for Disease Control and Prevention, and all participants completed informed consent.

Foot Disorders

Foot disorders were assessed using a validated physical examination of the foot to assess specific foot disorders.[12, 13] This instrument has been shown to have high validity when compared to podiatric examination and to have excellent reliability in large cohort studies.[12, 13] Using an atlas of pictorial representations of each foot disorder, two trained clinical examiners performed the foot examination to determine the presence or absence of hallux valgus, overlapping toes, hammer toes, claw toes, Morton's neuroma, Tailor's bunion, overlapping toes, and plantar fasciitis. For example, hallux valgus was defined as ≥ 15°angular deviation of the hallux with respect to the first metatarsal bone toward the lesser toes and the appearance of a medial bony enlargement of the first metatarsal head. Inter-rater reliability of the two examiners was high for all foot disorder measures (kappas = 0.72-1.00).

Foot Function

In a large epidemiologic study, ensuring clinical diagnoses across examiners and within each examiner over time in a large study would be immensely challenging when using clinical criteria to categorize foot type. Due to time constraints in a large, epidemiologic study of this size (1466 people), we chose to use plantar pressure data to approximate what would be found on clinical exam.[14, 25] Plantar pressure data were collected with a Tekscan Matscan System (Tekscan Inc, Boston, MA), which has shown moderate to good reliability.[28] Participants walked at their normal, self-selected pace, and scans were collected when the second step landed on the foot mat.[19] For each foot, two trials were collected.

The Center of Pressure Excursion Index (CPEI), a measure calculated from the walking pressure scan data, measures dynamic foot pronation and supination.[26] CPEI can be used to discriminate clinical foot types of planus and rectus. [26] The CPEI value is determined by: 1) drawing a line from the first and last center of pressure data points of the foot, 2) measuring

the distance between this line and the center of pressure in the anterior third of the foot, and 3) dividing the distance between the lines and the center of pressure by the forefoot width. A more pronated foot is suggested by a lower CPEI value, while a more supinated foot is indicated by a higher CPEI value.[26] The mean CPEI value for the two walking trials was used in analyses. Based on quintiles from another population-based study (Framingham Foot Study), CPEI cutoff values were set *a priori*.[6] The CPEI values were categorized as ≤7.3 for over-pronated foot, ≥21.0 for over-supinated foot, and >7.3 to <21.0 for the referent category.

Demographic and Clinical Characteristics

At the time of the clinical exam, age in years, sex, race (African American and Caucasian), weight (using a balance beam scale) and height (without shoes using a calibrated stadiometer) were recorded. Body mass index (BMI) was calculated as weight in kilograms per height in meters squared (kg/m^2). BMI was categorized into normal weight (<25 kg/m^2), overweight (25-<30 kg/m^2), and obese (30+ kg/m^2).

Analysis

Distributions of age, BMI, race, sex, foot disorder, and foot function were calculated. Because of the interest in differences of foot disorder and foot function associations by race and by BMI, chi-square statistics for categorical variables and t-test statistics for continuous variables were used for comparisons of age, sex, foot disorders, and foot function in African Americans versus Caucasians and across each BMI category. The unit of analysis was the foot. Separate crude and adjusted multivariate logistic regression models using generalized estimating equations were used to estimate the association between foot function and each foot disorder, controlling for age, BMI, race, and sex (95% confidence intervals not containing OR of 1.0 were considered statistically significant, corresponding to a $p<0.05$ for main effects). Statistical interaction of foot function and age, BMI categories, race, or sex were examined, with a p-value <0.10 considered statistically significant, as this p-value accounts for a product term of the interaction. Analyses were stratified by race and BMI categories.

RESULTS

Of the 1,695 Johnston County Osteoarthritis Project participants who attended the clinical exam visit, 1,466 participants had available foot exam and foot mat data (Figure 1). Nearly two-thirds of participants were women, 29.5% were African American, and on average, participants were older adults (mean age = 68.5 years) and obese (mean BMI = 31.2kg/m^2; Table 1). Of these participants, 1,425 had bilateral foot pressure data and 41 had unilateral foot pressure data (individuals for whom only one foot had valid data with other foot data missing due to missing or improbable values) for a total of 2,891 feet available for analyses (Figure 1). The CPEI data for the first and second trials were moderately correlated (Pearson correlation = 0.51). Approximately 14% of feet were over-pronated and 20% were over-supinated (Table 1). The most common foot disorders were hallux valgus (57.1%), overlapping toes (27.1%), and hammer toes (25.9%), while Morton's neuromas, Tailor's bunions, plantar fasciitis and claw toes were infrequent (Table 1).

Primary Objective: Foot Function and Foot Disorders in Total Sample

Results of unadjusted and adjusted analyses of the relationships between foot function and foot disorders for the total sample are summarized in Table 2. An over-pronated foot was associated with hallux valgus compared to the referent (adjusted odds ratio [aOR] 1.36, 95% confidence interval [CI] 1.13-1.65), and this foot function also was associated with overlapping toes (aOR 1.36, 95% CI 1.12-1.64). An over-supinated foot was inversely associated with hallux valgus compared to the referent (aOR 0.85, 95% CI 0.74-0.97).

Secondary Objective: Foot Function and Foot Disorders by Race and by BMI

Interactions between foot function and age, race, gender, and BMI categories were not statistically significant. However, patterns of differing estimates were noted by race (Table 3), with an over-supinated foot being associated with plantar fasciitis in Caucasians only, and by BMI category (Table 4). An over-pronated foot was associated with overlapping toes among the overweight and obese, while an over-supinated foot was inversely associated with hallux valgus among the obese.

DISCUSSION

Foot function was associated with several musculoskeletal foot disorders in this study. Results of this study supported clinical observations of an association between musculoskeletal foot disorders and a pronated foot. Despite expectations, associations between foot function and foot disorders did not vary significantly by race and obesity. Nevertheless, the pattern of associations among the over-pronated foot and certain musculoskeletal foot disorders among those who were overweight or obese suggested a need for further investigation to determine whether those with an over-pronated foot and greater than normal weight might be a group to target for future interventions.

Prior studies suggested either positive associations or no associations between a pronated foot and hallux valgus or overlapping toes.[11, 17, 18] Several results of the present study are comparable to those reported in another population study,[11] which examined foot disorders and foot function using the same measurements as our study in 3189 adults from the population-based Framingham Foot Study cohort (mean age 66 years, mean BMI of 28.4 kg/m^2, 56% women, Caucasians only). Pronated feet were associated with hallux valgus in both studies, but these results were not statistically significant in the Framingham study (aOR 1.08, 95% CI 0.95-1.22; Johnston County: aOR 1.36, 95% CI 1.13-1.65). Differences in the characteristics of the two cohorts may account for this discrepancy since hallux valgus was considerably more common in Johnston County than Framingham (57% versus 26%, respectively), potentially due to the greater proportion of women and African Americans in our study. Both studies reported that hallux valgus was less likely in supinated feet (Framingham: aOR 0.82, 95% 0.71-0.94; Johnston County: aOR 0.85, 95% CI 0.74-0.97) and that overlapping toes were associated with pronated feet (Framingham: aOR 1.40, 95% CI 1.08-1.80, Johnston County: aOR 1.36, 95% CI 1.12-1.64).

Associations between foot function and lesser toe deformities other than overlapping toes were not observed in this study. Although statistical power was adequate to clearly detect

relationships for hallux valgus, hammer toes, and overlapping toes (able to detect OR of 1.3 or greater), there was less power to detect differences for the lower prevalence foot disorders of Morton's neuromas, Tailor's bunions, plantar fasciitis, and claw toes (able to detect OR of 2.1 or greater). A previous review has suggested an association between pronated foot and Tailor's bunions. [2] Examining associations across populations, possibly using meta-analysis, may be a method to enhance sample size and reveal potential relationships.

The multiple strengths of this study include that it is community-based; consists of African American and Caucasian men and women; includes individuals who are normal weight, overweight, and obese; and foot function is based on quantitative, biomechanical measures. Additionally, participants completed the foot pressure scans twice for each foot and average values of foot pressure measures were used for determination of foot function. Analyses were foot-based as foot function may differ by foot within the same individual, and generalized estimating equations accommodated the correlated data between feet within an individual. An important limitation of this study is that the data were cross-sectional, and a temporal relationship or causality between foot function and foot disorders cannot be assumed. Associations between foot function and foot disorders could be multi-directional, where foot function may lead to foot deformities, a musculoskeletal foot disorder may result in biomechanical changes of the foot, or interplay between musculoskeletal foot disorders and foot function may accelerate the worsening of both conditions. A longitudinal analysis would aid in delineating the potential complexities of the foot function – foot disorder relationship, and this is a future step for our research as we are currently collecting follow-up foot data in the Johnston County Osteoarthritis Project. This study did not examine concomitant foot disorders, and the two disorders associated with a pronated foot (hallux valgus and overlapping toes) may occur together, especially if an individual wears shoes with inadequate toe room. Shoe wear data were not available for this analysis, and potentially, shoes may explain some observed associations. Hafer et al. in 2013 found that 5 walking trials were preferable to obtain a stable estimate for plantar pressure data.[10] In our current epidemiologic study, we obtained two walking trials due to time constraints in our multiphasic examination. However, as noted previously,[11] while we expect some measurement error with the plantar pressure system, the large numbers of participants should balance out the random misclassification from non-precise sensors and gait variability. Thus, while precision may be affected, this variability will not produce a different answer to our study questions, only a difference in precision.[23]

Also, CPEI categories may not correspond exactly with clinical definitions of foot function, and some participants with pronated or supinated foot may have been included in the referent group. However, the strength of our CPEI categories is that our cutoff values are based on population-based data, and the most extreme categories (over-pronated and over-supinated foot) include those that truly have these foot types. The clinical value of the CPEI categories is that they clearly show pronation and supination, allowing for a focused examination of disorders that may accompany these foot functions when they are more extreme. The findings in this study suggest strong associations between foot function and foot disorders.

In summary, foot function is associated with specific foot disorders in this bi-racial, community-based study. The associations reported in this large population of older adults support clinical observations of patients. These findings extend beyond clinical inferences as our study was based in the population of older men and women *who were not seeking clinical intervention*. Thus, both in clinical patients as well as in the community of older adults, approaches that treat both the foot disorder and the pronated/supinated foot are needed. The inference may be that the pre-clinical need for combined approaches to foot disorders and foot function are prevalent and linked even before persons in the community become clinical patients who are seeking medical relief from interventions by their health care providers. This study is cross-sectional and thus does not clarify whether the over-pronated or over-supinated foot occurs before or after (as a consequence of) the foot disorders, and future research should examine this temporal relationship through longitudinal analysis.

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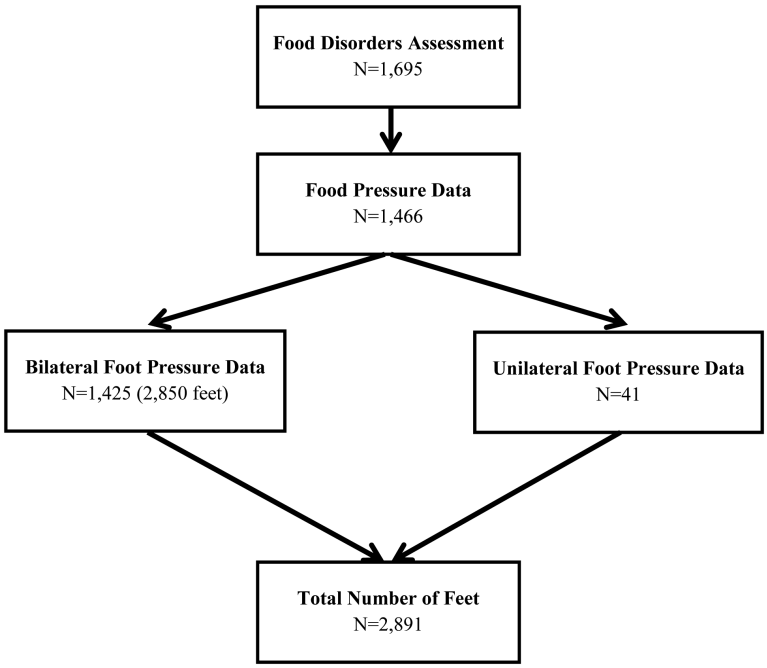

Figure 1.
Available Data for Analyses.

Table 1

Characteristics of Sample.

Participants (N=1,466)	**Characteristic**	**Mean (Standard Deviation)**
	Age (years)	68.5 (8.9)
	Body mass index (kg/m^2)	31.2 (6.8)
		N (%)
	Women	985 (67.2)
	African American	432 (29.5)
Feet (N=2,891)	**Characteristic**	**N (%)**
	Over-Pronated Foot Function	401 (13.9)
	Over-Supinated Foot Function	568 (19.7)
	Hallux Valgus	1651 (57.1)
	Overlapping Toes	784 (27.1)
	Hammer Toes	748 (25.9)
	Morton’s Neuroma	174 (6.0)
	Tailor’s Bunion	155 (5.4)
	Plantar Fasciitis	98 (3.4)
	Claw Toes	60 (2.1)

Table 2

Relation of Foot Function and Foot Disorder, Total Sample (Odds Ratio [OR] and 95% Confidence Interval [CI]).

Foot Disorder	Foot Function	% Foot disorder by Foot Function	Unadjusted OR (95% CI)	Adjusted* OR (95% CI)
Hallux Valgus	Over-Pronated	69.1	1.41 (1.17-1.70)	1.36 (1.13-1.65)
	Neutral	57.0	1.00	1.00
	Over-Supinated	49.1	0.85 (0.74-0.96)	0.85 (0.74-0.97)
Overlapping Toes	Over-Pronated	33.9	1.38 (1.15-1.67)	1.36 (1.12-1.64)
	Neutral	26.0	1.00	1.00
	Over-Supinated	26.1	0.97 (0.80-1.18)	0.97 (0.80-1.18)
Hammer Toes	Over-Pronated	26.7	0.96 (0.75-1.22)	0.89 (0.69-1.15)
	Neutral	25.4	1.00	1.00
	Over-Supinated	26.8	0.98 (0.80-1.20)	1.00 (0.81-1.23)
Morton’s Neuroma	Over-Pronated	4.7	0.76 (0.48-1.20)	0.79 (0.49-1.25)
	Neutral	6.0	1.00	1.00
	Over-Supinated	7.0	1.14 (0.84-1.53)	1.11 (0.82-1.50)
Tailor’s Bunions	Over-Pronated	9.0	1.14 (0.86-1.51)	1.23 (0.93-1.62)
	Neutral	4.8	1.00	1.00
	Over-Supinated	4.6	0.85 (0.59-1.22)	0.85 (0.60-1.22)
Plantar Fasciitis	Over-Pronated	3.5	0.92 (0.50-1.70)	0.98 (0.53-1.82)
	Neutral	3.3	1.00	1.00
	Over-Supinated	3.5	1.14 (0.78-1.67)	1.13 (0.76-1.67)
Claw Toes	Over-Pronated	1.8	0.75 (0.37-1.52)	0.69 (0.34-1.42)
	Neutral	2.2	1.00	1.00
	Over-Supinated	1.9	0.93 (0.51-1.69)	0.89 (0.48-1.64)

*Adjusted for age, body mass index, gender, and race

Table 3

Relation of Foot Function and Foot Disorder, by Race (Odds Ratio [OR] and 95% Confidence Interval [CI]).

		Adjusted* OR (95% CI)	
Foot Disorder	**Foot Function**	**Caucasian**	**African American**
Hallux Valgus	Over-Pronated	1.27 (1.02, 1.59)	1.65 (1.10, 2.46)
	Neutral	1.00	1.00
	Over-Supinated	0.85 (0.72, 0.99)	0.86 (0.67, 1.09)
Overlapping Toes	Over-Pronated	1.32 (1.05, 1.66)	1.48 (1.05, 2.07)
	Neutral	1.00	1.00
	Over-Supinated	0.88 (0.70, 1.11)	1.23 (0.84, 1.79)
Hammer Toes	Over-Pronated	1.00 (0.72, 1.40)	0.71 (0.49, 1.02)
	Neutral	1.00	1.00
	Over-Supinated	1.18 (0.92,1.52)	0.70 (0.49, 1.01)
Morton's Neuroma	Over-Pronated	0.87 (0.52, 1.43)	0.56 (0.18, 1.76)
	Neutral	1.00	1.00
	Over-Supinated	1.01 (0.71, 1.42)	1.37 (0.77,2.41)
Tailor's Bunions	Over-Pronated	1.05 (0.81, 1.37)	-
	Neutral	1.00	-
	Over-Supinated	0.80 (0.56, 1.14)	-
Plantar Fasciitis	Over-Pronated	0.90 (0.41, 1.97)	1.00 (0.35, 2.85)
	Neutral	1.00	1.00
	Over-Supinated	1.51 (1.02, 2.25)	0.35 (0.11, 1.10)
Claw Toes	Over-Pronated	0.86 (0.38, 1.94)	0.62 (0.19,2.08)
	Neutral	1.00	1.00
	Over-Supinated	1.07 (0.59, 1.94)	0.72 (0.22, 2.30)

*Adjusted for age, body mass index, and gender

Table 4

Relation of Foot Function and Foot Disorder, by Body Mass Index (Odds Ratio [OR] and 95% Confidence Interval [CI]).

		Adjusted* OR (95% CI)		
Foot Disorder	**Foot Function**	**Normal Weight (BMI < 25 kg/m^2)**	**Overweight (BMI 25-<30 kg/m^2)**	**Obese (BMI≥30kg/m^2)**
Hallux Valgus	Over-Pronated	1.41 (0.88, 2.24)	1.25 (0.87, 1.79)	1.44 (1.11, 1.86)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.92 (0.66, 1.27)	0.94 (0.75, 1.16)	0.78 (0.64, 0.95)
Overlapping Toes	Over-Pronated	0.99 (0.65, 1.51)	1.49 (1.05, 2.10)	1.45 (1.12, 1.88)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.87 (0.57, 1.34)	1.13 (0.77, 1.67)	0.93 (0.71, 1.21)
Hammer Toes	Over-Pronated	0.42 (0.22, 0.80)	1.39 (0.91, 2.13)	0.85 (0.59, 1.23)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.64 (0.36, 1.15)	1.35 (0.95, 1.91)	0.94 (0.71, 1.24)
Morton's Neuroma	Over-Pronated	0.97 (0.30, 3.15)	1.05 (0.54, 2.04)	0.54 (0.24, 1.22)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.95 (0.50, 1.78)	1.39 (0.84, 2.29)	1.05 (0.67, 1.64)
Tailor's Bunions	Over-Pronated	1.69 (0.97, 2.92)	1.30 (0.95, 1.76)	0.77 (0.43, 1.36)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.97 (0.56, 1.65)	1.20 (0.62, 2.33)	0.51 (0.27, 0.97)
Plantar Fasciitis	Over-Pronated	-	1.29 (0.40, 4.16)	0.98 (0.52, 1.84)
	Neutral	1.00	1.00	1.00
	Over-Supinated	-	1.09 (0.48, 2.51)	1.24 (0.76, 2.03)
Claw Toes	Over-Pronated	1.01 (0.29, 3.44)	0.63 (0.23, 1.70)	0.42 (0.06, 2.98)
	Neutral	1.00	1.00	1.00
	Over-Supinated	0.81 (0.22, 2.99)	0.54 (0.25, 1.18)	1.27 (0.43, 3.71)

† BMI = body mass index

*Adjusted for age, gender, and race